Gravitational Radius Stabilization
in Supersymmetric Warped Compactification

Nobuhito Maru[a] [1] and Nobuchika Okada[b] [2]

[a] *Theoretical Physics Laboratory, RIKEN,*

2-1 Hirosawa, Wako, Saitama 351-0198, Japan

[b] *Theory Division, KEK, Oho 1-1, Tsukuba, Ibaraki 305-0801, Japan*

Department of Particle and Nuclear Physics, The Graduate University

for Advanced Studies (Sokendai), Oho 1-1, Tsukuba, Ibaraki 305-0801, Japan

Abstract

We examine the possibility of the extra dimensional radius stabilization with only the gravity multiplet in the bulk and some couplings at orbifold fixed points in a supersymmetric Randall-Sundrum model. Unfortunately, we find that the radius cannot be stabilized in all the cases we consider. Depending on parameters in the model, the fifth dimension collapses or its radius goes to infinity. While the former case is theoretically disastrous, the latter implies that the so-called "RS II" model is automatically realized in our setup. Although the radius is not stabilized, there is nothing wrong with the resultant RS II model, because it is not only phenomenologically viable but also free from the gauge hierarchy problem thanks to its supersymmetric extension.

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[1] E-mail: maru@riken.jp

[2] E-mail: okadan@post.kek.jp

Brane world scenario is well motivated to solve the gauge hierarchy problem without supersymmetry (SUSY). Remarkable examples are models with large (flat) extra dimensions [1, 2, 3] and the model with a warped extra dimension [4]. Alternatively, an extension to SUSY brane world scenario is also well motivated to solve SUSY flavor problem geometrically [5, 6]. Irrespective of the existence of SUSY or not, the radius stabilization is a generic important issue to construct realistic brane world scenarios. So far, many models have been proposed in non-SUSY case [7, 8, 9, 10, 11, 12, 13] and SUSY case [6, 14, 15, 16, 17, 18, 19, 20, 21, 13]. All these models introduce new bulk fields in addition to gravity, which play the crucial role to succeed the radius stabilization. Introduction of such bulk fields makes the model complicated and somewhat artificial. It would be nice if the radius can be stabilized via only the gravitational effects with only gravity in the bulk and some couplings among the radius moduli (radion) and the brane fields. This possibility through the Casimir energy was examined many years ago and found to be failed [22]. In models with flat extra dimensions, the existence of the brane does not make the situation better since there is no coupling among the radion and brane fields at tree level. On the other hand, in the model with warped extra dimension, the brane fields can couple to the radion at tree level and such couplings may play an important role for the radius stabilization with only gravitational effects. In this paper, we examine this possibility in a SUSY Randall-Sundrum (RS) model [23, 24, 25, 26].

Let us consider the SUSY RS model with the AdS$_5$ metric

$$ds^2 = e^{-2kry}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 dy^2 \ (\mu, \nu = 0, 1, 2, 3), \tag{1}$$

where k, x, y, r are an AdS$_5$ curvature scale, the coordinates of four dimensions, the angle and the radius of the fifth dimension, $0 \leq y \leq \pi$, respectively. Here the AdS$_5$ curvature scale should be small compared to the five dimensional Planck scale M_5, so that the above metric can be trusted. In our setup, the bulk field is only the gravity multiplet and the other fields reside only on branes at $y = 0, \pi$ being S^1/Z_2 orbifold fixed points.

As the simplest setup to arise the nontrivial radion potential, let us first examine the case with constant superpotentials on the both boundary branes. In the superconformal framework, the four dimensional effective Lagrangian below the Kaluza-Klein (KK) scale

is given by [27]

$$\mathcal{L} = \int d^4\theta \left[-\frac{3M_5^3}{k}(\phi^\dagger\phi - \omega^\dagger\omega) \right] + \left[\int d^2\theta(\phi^3 W_0 + \omega^3 W_\pi) + \text{h.c.} \right], \tag{2}$$

where ϕ denotes the compensating multiplet $\phi = 1 + \theta^2 F_\phi$, $\omega \equiv \phi e^{-k\pi T}$ (T : the radion multiplet, $\text{Re}T = r$), and $W_{0,\pi}$ are the constant superpotentials localized at $y = 0, \pi$. The Lagrangian for auxiliary fields can be read off as

$$\mathcal{L}_{\text{aux}} = F_\phi^\dagger \left\{ -\frac{3M_5^3}{k}F_\phi + 3W_0^\dagger \right\} + F_\omega^\dagger \left\{ \frac{3M_5^3}{k}F_\omega + 3(\omega^2 W_\pi)^\dagger \right\}$$
$$+ 3F_\phi W_0 + 3F_\omega \omega^2 W_\pi. \tag{3}$$

Equations of motion for auxiliary fields give solutions

$$F_\phi = \frac{k}{M_5^3}W_0^\dagger, \quad F_\omega = -\frac{k}{M_5^3}(\omega^2 W_\pi)^\dagger. \tag{4}$$

Substituting F_ϕ and F_ω into (3), the radion potential is obtained as

$$V = -3F_\phi W_0 - 3F_\omega \omega^2 W_\pi, \tag{5}$$
$$= \frac{3k}{M_5^3}\left(-|W_0|^2 + |\omega^2 W_\pi|^2 \right), \tag{6}$$

which implies that the radius goes to infinity $\omega = 0$. For consistency with the metric, namely the flat 4 dimensional spacetime metric, the cosmological constant should vanish, so that W_0 should be zero or a (global) SUSY breaking source to cancel the negative cosmological constant should be added. Then, the model automatically reduces to the so-called "RS II" model [28].

The next possibility to stabilize the radius without introducing any bulk field is that there exit SUSY breaking fields localized at $y = \pi$ brane. Note that any brane field at $y = 0$ has no effects for the radius stabilization since it does not couple to the radion. Thus, two parts involving ϕ and ω are completely separated in the Lagrangian, and the part relevant to the radion potential is

$$\mathcal{L} = \int d^4\theta \left[\left(\frac{3M_5^3}{k} + K(X^\dagger, X) \right) \omega^\dagger\omega \right] + \left[\int d^2\theta \omega^3 W(X) + \text{h.c.} \right], \tag{7}$$

where X is a chiral multiplet localized at $y = \pi$ brane, their Kähler potential and superpotential are denoted as $K(X^\dagger, X)$ and $W(X)$. The auxiliary components of the above

Lagrangian can be extracted as

$$\mathcal{L}_{\text{aux}} = F_\omega^\dagger \left(\left(\frac{3M_5^3}{k} + K \right) F_\omega + K_X F_X \omega + 3(\omega^2 W)^\dagger \right)$$
$$+ F_X^\dagger \left(K_{X^\dagger} F_\omega \omega^\dagger + K_{XX^\dagger} F_X |\omega|^2 + (\omega^3 W_X)^\dagger \right) + 3\omega^2 F_\omega W + \omega^3 W_X F_X, \quad (8)$$

where K_X etc. are the shorthand notation of the derivative of K with respect to X etc. Equations of motion for the auxiliary fields give solutions,

$$\begin{pmatrix} F_\omega \\ F_X \end{pmatrix} = \frac{1}{|B|^2 - AC} \begin{pmatrix} 3C(\omega^2 W)^\dagger - B(\omega^3 W_X)^\dagger \\ -3B^\dagger(\omega^2 W)^\dagger + A(\omega^3 W_X)^\dagger \end{pmatrix}, \quad (9)$$

where

$$A = \frac{3M_5^3}{k} + K, \quad (10)$$

$$B = K_X \omega, \quad (11)$$

$$C = K_{XX^\dagger} |\omega|^2. \quad (12)$$

Substituting these into $\mathcal{L}_{\text{aux}}$, we obtain the radion potential

$$V = -3\omega^2 F_\omega W(X) - \omega^3 W_X F_X, \quad (13)$$
$$= \frac{|\omega|^4}{AC - |B|^2} \left[C \left| 3W(X)^\dagger - \frac{BW_X^\dagger}{K_{XX^\dagger} \omega} \right|^2 + C^{-1} \left(AC - |B|^2 \right) |\omega|^2 |W_X|^2 \right]. \quad (14)$$

The general argument is the following. The Lagrangian we consider has the same form as the global SUSY one, so that the radion potential is semi-positive definite. Noting that the potential is proportional to ω, we can conclude that the global minimum of the potential $V = 0$ is always realized at $\omega = 0$. Therefore, the radius goes to infinity ($\omega = 0$) and the model reduces to the SUSY RS II model again. Here we have used the fact that the Kähler metric should be positive, namely $AC - |B|^2 > 0$ and $A, C > 0$ in the explicit form of the potential (14), otherwise the system itself is unstable. [3]

The final possibility we consider is to include quantum effects, namely 1-loop Casimir energy which has been recently calculated [29] in the different context. We expect that the radius can stabilized in this case, since there are nontrivial radius dependences in the potential at tree and one-loop levels.[4] In this case, the Lagrangian becomes complicated

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[3]Even if $AC - |B|^2 < 0$, one can easily show that the vacuum at the finite radius is the local minimum.

[4]Even if we find that the Casimir effect works so as to stabilize the radius, we have to be careful for our treatment because the effect is the corrections of the next order. As will be seen later, we come to the same result as in the tree level when the Casimir effects are taken into account.

since the mixing term between ϕ and ω in the Kähler potential is induced by the 1-loop Casimir effects. The Lagrangian we examine is given by

$$\mathcal{L} = \int d^4\theta K + \left\{ \int d^2\theta W + h.c. \right\}, \tag{15}$$

where

$$K = -\frac{3M_5^3}{k}(\phi^\dagger\phi - \omega^\dagger\omega) + \frac{ck^2}{4\pi^2}\frac{(\omega^\dagger\omega)^2}{\phi^\dagger\phi}, \quad W = \phi^3 W_0 + \omega^3 W_\pi. \tag{16}$$

The last term in the Kähler potential is the new term induced by 1-loop corrections[5] and $c \simeq 1.165$ is the numerical number [29]. The Lagrangian for auxiliary fields can be read off as

$$\begin{aligned}
\mathcal{L}_{\text{aux}} &= F_\phi^\dagger \left(K_{\phi^\dagger\phi} F_\phi + K_{\phi^\dagger\omega} F_\omega + 3W_0^\dagger \right) \\
&+ F_\omega^\dagger \left(K_{\omega^\dagger\phi} F_\phi + K_{\omega^\dagger\omega} F_\omega + 3(\omega^2 W_\pi)^\dagger \right) + 3W_0 F_\phi + 3\omega^2 W_\pi F_\omega,
\end{aligned} \tag{17}$$

where $K_{\phi^\dagger\phi}$, $K_{\phi^\dagger\omega}$ etc. are explicitly described as follows:

$$\begin{aligned}
K_{\phi^\dagger\phi} &= \left.\frac{\partial^2 K}{\partial\phi^\dagger\partial\phi}\right|_{\phi=1} = -\frac{3M_5^3}{k} + \frac{ck^2}{4\pi^2}(\omega^\dagger\omega)^2, \\
K_{\phi^\dagger\omega} &= \left(K_{\omega^\dagger\phi}\right)^\dagger = \left.\frac{\partial^2 K}{\partial\phi^\dagger\partial\omega}\right|_{\phi=1} = -\frac{ck^2}{2\pi^2}(\omega^\dagger\omega)\omega^\dagger, \\
K_{\omega^\dagger\omega} &= \left.\frac{\partial^2 K}{\partial\omega^\dagger\partial\omega}\right|_{\phi=1} = \frac{3M_5^3}{k} + \frac{ck^2}{\pi^2}(\omega^\dagger\omega).
\end{aligned} \tag{18}$$

Equations of motion for auxiliary fields give solutions,

$$F_\phi = \frac{k}{M_5^3}\left(1 + \tilde{c}(\omega^\dagger\omega) - \frac{\tilde{c}}{4}(\omega^\dagger\omega)^2\right)^{-1}\left[\left(1 + \tilde{c}(\omega^\dagger\omega)\right)W_0^\dagger + \frac{\tilde{c}}{2}(\omega^\dagger\omega)(\omega^3 W_\pi)^\dagger\right], \tag{19}$$

$$F_\omega = -\frac{k}{M_5^3}\left(1 + \tilde{c}(\omega^\dagger\omega) - \frac{\tilde{c}}{4}(\omega^\dagger\omega)^2\right)^{-1}\left[-\frac{\tilde{c}}{2}(\omega^\dagger\omega)\omega W_0^\dagger + \left(1 - \frac{\tilde{c}}{4}(\omega^\dagger\omega)^2\right)(\omega^2 W_\pi)^\dagger\right] \tag{20}$$

where $\tilde{c} = \frac{ck^3}{3\pi^2 M_5^3} \leq \frac{c}{3\pi^2} \ll 1$ for $k \leq M_5$. Substituting these into the radion potential, we obtain

$$\begin{aligned}
V &= -3W_0 F_\phi - 3\omega^2 W_\pi F_\omega, \tag{21} \\
&= \frac{3k}{M_5^3}\left(1 + \tilde{c}(\omega^\dagger\omega) - \frac{\tilde{c}}{4}(\omega^\dagger\omega)^2\right)^{-1} \\
&\times \left[-\left(1 + \tilde{c}(\omega^\dagger\omega)\right)|W_0|^2 + \left(1 - \frac{\tilde{c}}{4}(\omega^\dagger\omega)^2\right)(\omega^\dagger\omega)^2|W_\pi|^2\right. \\
&\left.- \frac{\tilde{c}}{2}(\omega^\dagger\omega)\left(W_0(\omega^3 W_\pi)^\dagger + W_0^\dagger(\omega^3 W_\pi)\right)\right]. \tag{22}
\end{aligned}$$

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[5]We consider only the simpler form in the strongly warped case, for simplicity.

Before analyzing the radion potential in detail, let us examine the radius stabilization for two special cases. The first is the case with $W_\pi = 0$. The radion potential is reduced to the form,

$$V = -\frac{3k}{M_5^3} \left(1 + \tilde{c}(\omega^\dagger \omega) - \frac{\tilde{c}}{4}(\omega^\dagger \omega)^2 \right)^{-1} \left(1 + \tilde{c}(\omega^\dagger \omega) \right) |W_0|^2 . \tag{23}$$

Since $\tilde{c} \ll 1$ and ω is defined in the range $0 \le \omega \le 1$, the potential has a minimum at $\omega = 1$. This means that the fifth dimension collapses. On the other hand, in the case with $W_0 = 0$, the radion potential is found to be

$$V = \frac{3k}{M_5^3} \left(1 + \tilde{c}(\omega^\dagger \omega) - \frac{\tilde{c}}{4}(\omega^\dagger \omega)^2 \right)^{-1} \left(1 - \frac{\tilde{c}}{4}(\omega^\dagger \omega)^2 \right) (\omega^\dagger \omega)^2 |W_\pi|^2 . \tag{24}$$

The potential minimum is realized at $\omega = 0$ and the potential energy is zero there, which means the fifth dimensional radius goes to infinity and the system becomes the SUSY RS II model. Since the above two cases come to opposite results, we may expect that the radius can be stabilized at $0 < \omega < 1$ if we introduce both non-zero W_0 and W_π.

Now let us examine the case with both non-zero constant superpotentials. Considering the form of the potential (22), we can start with both $W_{0,\pi}$ real and positive without loss of generality by an appropriate convention of the complex phase of ω. Parameterizing $\omega = xe^{i\theta/3}$ ($0 \le x = |\omega| \le 1$), θ-dependent part in the potential is given by

$$V \supset -\frac{3k}{M_5^3} \left(1 + \tilde{c}x^2 - \frac{\tilde{c}}{4}x^4 \right)^{-1} \left(\tilde{c}W_0 W_\pi x^5 \cos\theta \right) . \tag{25}$$

Thus, the potential minimum in θ-direction is realized at $\theta = 0$. For examining the potential minimum in x-direction, it is useful to rewrite the potential into the form,

$$\hat{V}(x) = \frac{V}{\frac{3k}{M_5^3} W_0^2} = f(x)^{-1} g(x), \tag{26}$$

where

$$
\begin{aligned}
f(x) &= 1 + \tilde{c}x^2 - \frac{\tilde{c}}{4}x^4, \\
g(x) &= -\left(1 + \tilde{c}x^2 \right) + \left(1 - \frac{\tilde{c}}{4}x^4 \right) x^4 a^2 - \tilde{c}x^5 a
\end{aligned}
\tag{27}
$$

with $a = W_\pi / W_0 > 0$. Since $f(x) > 0$ for $\tilde{c} \ll 1$ and $0 \le x \le 1$, the minimization condition is equivalent to the condition $fg_x - f_x g = 0$, where f_x etc. stand for df/dx etc.

For $0 < x < 1$, the condition is explicitly described as

$$
\begin{aligned}
\frac{fg_x - f_x g}{x^3} &= -\left(\tilde{c} + \frac{\tilde{c}^2}{2}x^2\right) + \left(-5\tilde{c}x - 3\tilde{c}^2 x^3 + \frac{\tilde{c}^2}{4}x^5\right) a \\
&+ \left(4 + 2\tilde{c}x^2 - 2\tilde{c}x^4 - \frac{3\tilde{c}^2}{2}x^6 + \frac{\tilde{c}^2}{4}x^8\right) a^2 \\
&\simeq -\tilde{c} - 5\tilde{c}ax + 4a^2 = 0,
\end{aligned}
\tag{28}
$$

where we have used $\tilde{c} \ll 1$ and $0 < x < 1$ in the approximation formula. The minimization condition is satisfied by $x \simeq x_0 = (4a^2 - \tilde{c})/(5\tilde{c}a)$. Since the second derivative of the potential at $x = x_0$ is given by $\hat{V}_{xx}|_{x=x_0} = f^{-2}(fg_{xx} - f_{xx}g)|_{x=x_0}$, the sign of V_{xx} at $x = x_0$ is determined by $(fg_{xx} - f_{xx}g)|_{x=x_0}$. Its explicit form is described as

$$
\begin{aligned}
\frac{fg_{xx} - f_{xx}g|_{x=x_0}}{x_0^2} &= -\left(3\tilde{c} + \frac{5\tilde{c}^2}{2}x_0^2\right) + \left(-20\tilde{c}x_0 - 18\tilde{c}^2 x_0^3 + 2\tilde{c}^2 x_0^5\right) a \\
&+ \left(12 + 10\tilde{c}x_0^2 - 14\tilde{c}x_0^4 - \frac{27\tilde{c}^2}{2}x_0^6 + \frac{11\tilde{c}^2}{4}x_0^8\right) a^2 \\
&\simeq -3\tilde{c} - 20\tilde{c}ax_0 + 12a^2 = -5\tilde{c}ax_0 < 0.
\end{aligned}
\tag{29}
$$

Therefore, the potential has its maximum at $x = x_0$ and the radius is not stabilized. The global potential minimum is realized at $x = 0$ or $x = 1$ depending on the value a. By straightforward calculations, we can find the global minimum at $x = 0$ ($x = 1$) for $a \geq a_c$ ($a \leq a_c$), where $a_c = \frac{2\tilde{c} + \sqrt{3\tilde{c}^2 + 4\tilde{c}}}{4 - \tilde{c}}$. Even in either case, since the vacuum energy is found to be negative, a global SUSY breaking source should be added to obtain the vanishing cosmological constant.

In summary, we have investigated whether the extra dimensional radius can be stabilized via only the gravitational effects in the SUSY Randall-Sundrum model. We have found that the radius cannot be stabilized even if we take into account the constant superpotentials on the branes, the couplings with the brane localized SUSY breaking field, and the 1-loop Casimir energy effects. Depending on the parameters in the model, the fifth dimension collapses or its radius goes to infinity. While the former case is theoretically disastrous, the latter implies that the RS II model can be automatically realized in our setup. Although the radius cannot be stabilized, there is nothing wrong with the resultant SUSY RS II model, because it is not only phenomenologically viable and also free from the gauge hierarchy problem thanks to its SUSY extension. Moreover, the RS II

model has an interesting aspect on cosmology. Its cosmological solution have been found to lead to a non-standard Friedmann equation, and the expansion rate can be altered in the early universe [30]. Some particle cosmological implications of the RS II cosmology have been discussed elsewhere [31, 32].

Finally, we give a comment on more complicated cases. Considering the Casimir effects (including higher order corrections) in the case with both boundary fields and their non-trivial Kähler potentials and superpotentials is the most general setup to examine the radius stabilization. Since, in this case, there are many mixing terms among all the fields including ϕ [29], it is very hard to analyze this case and get an definite conclusion. We have skipped this case in the paper. However, note that, if $k \ll M_5$, Casimir effects are negligible and we come to one of our conclusion in the paper.

Acknowledgments

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